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Review

Examination of knee sagittal plane movements with wearable sensors and their application to the clinic: A scoping review

Application of wearable sensors to the clinic

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Abstract

Aim: This study aimed to provide information about knee function by examining sagittal plane movements of the knee with wearable sensors, to summarize the growing literature to determine its clinical applications, and to provide an up-to-date overview.

Material and Methods: We performed a comprehensive search of PubMed, Google Scholar, IEEE, and Scopus databases using various combination of the keywords “knee”, “knee joint”, “wearable technology” and “wearable devices”. We have thoroughly searched the included studies and reference lists to get more devices and references and took the device name and manufacturer for each reference.

Results: It is important for knee-related wearable devices to capture the diversity of knee movements in daily activities. Misalignment of anatomical landmarks and axis of rotation, fast or slow movement, soft tissue artifact, and sensor flexibility can lead to inaccurate measurements.

Discussion: When the studies are examined, there is a rapid growth in this field and accurate and reliable measurements can be made with less error rates. Future studies should determine how to make the most valuable and accurate measurements for patients, reduce sensor complexity, and develop cost-effective models.

Keywords

Wearable Technology, Wearable Devices, Knee and Knee Joint

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Introduction

The knee is a frequently injured joint and the frequency of injury is increasing [1]. Clinically significant information obtained by monitoring the kinematic changes of the knee for clinical and research purposes is important for understanding the prognosis of diseases and also for evaluating rehabilitation practice [2]. Evaluation of sagittal plane movements of the knee joint is widely used to evaluate patient function and recovery [3]. This kinematic information is usually obtained with protractors or electro-goniometers and three-dimensional (3D) motion capture cameras. However, electrogoniometers analyze motion in two planes. Three-dimensional motion capture cameras, on the other hand, are considered the gold standard for motion capture, but require a laboratory environment, experienced personnel and cost [4]. Also, it is used only in a limited area, its evaluations are limited to short periods (1-2 hours) and often couldn't be done because of its high costs [5]. Considering the last ten years, significant progress has been made in the field of wearable technology [6]. Many researchers have developed technologies to assess knee health using wearable sensors, and approaches have focused primarily on sensor detection, knee kinematics or gait assessment [5, 7–9].

Wearable devices, often using magnetometers, accelerometers, and gyroscopes, can provide a higher level of information about joint motion, potentially related to the underlying pathophysiology or rehabilitation condition [5]. Accelerometers are common sensors found in wearable devices and can give acceleration as well as top speed [10]. Jiroscopes are another common sensor in wearable devices that detect angular accelerations [10]. Magnetometers are often combined with and complement accelerometers and gyroscopes to filter the direction of movements [10, 11]. However, İnertial Measurement Unit- based (IMU) approaches must use additional sensing units with accurate computational capability for signal processing and require regular calibration and modeling to reduce the effects of directional drift [12, 13].

The examination of sagittal plane movements of the knee joint seems to be useful for evaluating functionality and medical condition. Studies on sagittal plane movements of the knee have been done [5, 7–9], but the accuracy and reliability of existing devices have not been mentioned. This review aims to provide an up-to-date overview of “”Examination of Sagittal Plane Movements of the Knee with Wearable Sensors and Application to the Clinic”. Using the information in this review, informed and accurate device selections can be made for specific research objectives.

Material and Methods

We conducted a study to examine the movements of the knee in the sagittal plane with wearable sensors and to determine its application to the clinic. Between January 1, 2018 and August 20, 2021, we searched the following databases: PubMed, Google Scholar, IEEE, and Scopus. Due to advances in technology, we did not include older articles in the study.

We have thoroughly searched the included studies and reference lists to get more devices and references. The search strategy included medical topics (i.e. MeSH), terms and text words related to “knee”, “knee joint”, “wearables” and “wearable technology”. We took the device name and manufacturer for each reference.

Ethics Approval

This study is a scoping review of the literature and does not require ethical approval.

Results

The initial search resulted in 2,294 articles and we removed similar ones. We extracted 2,128 more articles based on inclusion and exclusion criteria. Finally, we reviewed the remaining 13 articles to examine the sagittal plane motion of the knee with wearable sensors and to determine their clinical application. A flow chart explaining the identified and included articles is given in articles. Inclusion and exclusion criteria are given below Figure 1.

Inclusion Criteria

- Studies involving the use of any combination of accelerometer, pedometer, or inertial measurement unit for the study of sagittal plane movements of the knee.
- Studies involving a least of n=10 knee patients.
- Works written in English
- Studies whose full text accessed
- Studies that provide accuracy and validity data

Exclusion Criteria

- Conference summaries.
- Book chapters
- Systematic reviews.
- Articles featuring animals, robotic assistive devices, orthoses, exoskeletons, or virtual reality environments
- Primary outcome measures; studies on heart rate, sleep or cognitive/emotional conditions, physical activity level
- Studies that only determine gait parameters and are used as an assistive device during surgery
- Studies describing published study protocols or abstracts.

The purpose, model and manufacturer, technology (sensor) and location characteristics of the studies examined are given in Table 1.

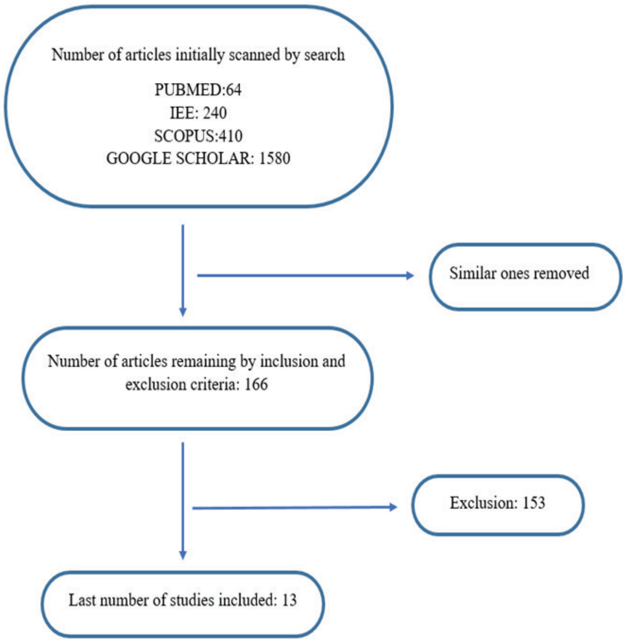
Number of articles initially scanned by search
PUBMED:64
IEE: 240
SCOPUS:410
GOOGLE SCHOLAR: 1580
Similar ones removed
Number of articles remaining by inclusion and exclusion criteria: 166
Exclusion: 153
Last number of studies included: 13

Figure 1. Flowchart describing the identified and included

Table 1. Purpose, model and manufacturer, technology (sensor) and location characteristics of the studies examined

	Purpose of the study	Model and manufacturer	Technology (Sensor)	Where is it fitted
[2]	Validating the ability of a novel wearable sensor system to measure peak knee sagittal angles during walking.			The front side of the right knee
[14]	Potentiometer embedded knee brace validation study	MHP24, Megatron Electronics, Putzbrunn, GERMAN	Potentiometer	To the side of the traditional knee pad
[15]	Validating WIS motion capture system against Optoelectronic beacon based motion capture system.	MTw Awinda, Xsens Technologies, Enschede, The Netherlands	Accelerometer-gyroscope	Thigh and tibia
[16]	Ensuring validation of MoJoXlab software	MoJoXlab (version 2018b; The MathWorks Inc)	3-D accelerometer, gyroscope and magnetometer	One on both upper thighs, one on both lower legs, one on the backs of both feet, and one on the sacrum
[17]	Evaluation of a sensor-based system to monitor the rehabilitation process after total knee replacement.	MPU6050	3-D accelerometer and gyroscope	Thigh and ankle
[18]	Validation of a fiber-based strain sensor for three-dimensional kinematic monitoring.		Strain Sensor	Ankle and knee
[19]	Validating the application of a low-cost wearable sensor by measuring peak knee extension.	LSM9DS0, FLORA 9-DOF, Adafruit, New York, NY	Accelerometer, gyroscope and magnetometer	10 cm away from the knee joint line; on the distal-lateral thigh and proximal-lateral shaft
[20]	To determine the validity of the gyroscope algorithm alone for calculating knee flexion/extension angles	in-house Multi-Axial Profile Recorder (MAPR) system	Gyroscope	Embedded in knee sleeves
[21]	Estimating joint angles using wearable IMUs during sit-to-stand exercise.	Wearable sensor JY-901B	Accelerometer and gyroscope	The body, thigh, head, neck, arms
[22]	Providing a reliable, efficient and cost-effective wearable sensor designed for long-term monitoring of joint kinematics		9-axis IMU-potentiometer	On the shaft near the ankle
[23]	Validating a soft robotic stretch (SRS) sensor embedded in a smart knee brace against a motion capture system focused on knee joint kinematics.	StretchSense™ SRS sensörü (Auckland, Yeni Zelanda)	SRS sensor	Front of knee pad
[24]	Validating the IMU-based knee angle measurement system with three exercises, determining the effect of visual feedback and qualitative experience of the user interface.	3-Space Bluetooth Sensor, Yost Labs, Portsmouth, OH, ABD	3-D accelerometer, gyroscope and magnetometer	Placed on the thigh and shaft equidistant from the middle of the patella
[25]	Evaluate the suitability of sensors for qualitative and quantitative motion analysis and determine the repeatability of the results.	Orthyo system (Aisens sp.z oo Poznan, Poland)	Accelerometer, gyroscope, magnetometer, barometer and thermometer	On the thigh and lower leg

Table 2. Accuracy and reliability and results of the measurement characteristics of the studies examined

	Accuracy and reliability	Results of the measurement
[2]	RMSE: 1.2(±0.4)° ICCs>0.8	These results demonstrate the sensor's ability to monitor knee apex sagittal angles with small margins of error, consistent with the gold standard system.
[14]	7.64° to 9.85° (n = 32) and 3.20° to 4.33° (n = 9) for RMSE 1 and 2 experiments, respectively.	The integration of the potentiometer built into the knee brace has proven robust over several hours of data tracking and is capable of measuring sagittal knee movement during various activities of daily living.
[15]	A perfect fit was found for the knee and hip sagittal plane angles. (r = 0.99, CMC = 0.98)	The WIS motion capture system has demonstrated near-perfect validity in the evaluation of complex movements commonly used in rehabilitation after anterior cruciate ligament injury.
[16]	CC and NRMSE values: 0.99 (SD 0.01) and 0.042 (SD 0.025) for the sagittal plane; 0.88 (SD 0.048) and 0.18 (SD 0.078) for the frontal plane; 0.85 (SD 0.027) and 0.23 (SD 0.065) for the transverse plane.	MoJoXlab has been shown to be able to accurately calculate joint angles for comparable motion analysis applications in walking, squatting, and jumping in healthy and anterior cruciate ligament reconstruction individuals.
[17]	Average absolute oscillation errors; 1.65° to 3.27°. Their accuracy at different angular velocities; 98.09% to 96.16%	Experimental results confirmed that the proposed system is effective and comparable to professional equipment.
[18]	RMSE: 2.32	A reliable kinematic motion capture device has been produced that uses deep learning architecture to generalize cross-participant data beyond what is currently available.
[19]	RMSE : 2,6	It demonstrates that the sensor paradigm is a viable tool for monitoring patient progress throughout physical therapy.
[20]	The RMSE of the GO algorithm was within 5-7°. Minimum detectable change of 7.33° and 6.39° at peak swing flexion and ICCs were 0.57 and 0.62.	The new GO algorithm can calculate knee angle using only angular velocity data and gait phase information from IMUs attached above and below the knee joint.
[21]	Knee joint angle RMSE :0.087	The developed prototype of the wearable sensor system provided a methodological reference for evaluating the functional rehabilitation status of patients who cannot perform sit-to-stand exercises.
[22]	RMSE: 5.0_{o}±1.00	The proposed wearable device can accurately predict knee flexion/extension angles during movement at various walking speeds.
[23]	For knee flexion/extension: R 2 = 0.799, RMSE = 5.470, MAE = 4.560	The smart knee pad showed greater fit and accuracy during weight-bearing squats and lower fit and accuracy during non-weight-bearing knee flexion/extension and gait.
[24]	ICC (IMUs and OptiTrack): Heel shift :0.58 Short arc quadriceps exercise:0.86 Sit-to-stand exercise: 0.80	This study demonstrated the potential of interACTION to measure range of motion during rehabilitation exercises, and visual feedback significantly improved the participant's ability to perform exercises accurately.
[25]	Squared errors (SSE) LEFT:11 ± 11/ 10 ± 9 Squared errors (SSE) RIGHT: 8 ± 8/8 ± 7	It has been stated that the test method examined may be of high importance for functional evaluations of the knee joint.

(RMSE= Root Mean Square Error; ICC= Intra-Class Correlation Coefficients; GO= Gyroscope Only Algorithm; MAPR= Multi-Axial Profile Recorder; CF= Complimentary Filter Algorithm; GOMAPR= GO algorithm knee angle estimate using MAPR data; GOOpal= GO algorithm knee angle estimate using Opal data; CFMAPR= CF algorithm knee angle estimate using MAPR data; CFOpal= CF algorithm knee angle estimate using Opal data; EKFMAPR= Extended Kalman Filter knee angle estimate using MAPR data; SSE= The Sum of Squared Errors; MAE= Mean Absolute Error; CC= Cross-Correlation; NRMSE= Normalized Root Mean Square Error; SD= Standard Devıatıon; CMC= Coefficient of Multiple Correlation; IMU= Inertial Measurement Unit; R2= R-squared; n= Number; s= Second; r= Pearson's Correlation Coefficient)

Table 3. Limitations of the studies reviewed

	Limitations
[2]	Requires a special calibration, the sensor gives erroneous outputs in the low range of the knee angle.
[14]	The fact that it measures knee movement in only one plane, the risk of slipping from clothing, the calibration process, and the increased humidity caused by perspiration during physical activity affect the measurement accuracy.
[15]	The speed of the athletes was not controlled, the comparison of systems was based only on the kinematic data of healthy athletes, and a single full-body configuration was adopted for the WIS system.
[16]	There is a difference in the number of trials available for data analysis between healthy and anterior cruciate ligament reconstruction participants.
[17]	Although the developed sensor devices are small and light, they must be placed in a shell and Velcro and an elastic belt are required to attach them to the leg.
[18]	It did not include people of different genders, sizes, and ages, and testing times were limited.
[19]	Only healthy young adults participated and the body mass index (23.8 ± 3.7) was lower than many patient populations, including those undergoing total knee arthroplasty, a single investigator deployed the sensor in all research subjects, the sample size was small.
[20]	May not be suitable for subject populations that cannot fully extend the knee joint.
[21]	Small sample size
[22]	It is the inconsistency of the algorithm used in their previous work in reporting performance when applied to this dataset.
[23]	For participants with different body anthropometry who have used a one-size-fits-all knee brace, the design and construction of the knee brace did not provide sufficient stability to hold the SRS sensor in place
[24]	The sample size was small, the sample group consisted of young healthy volunteers and was based on the experience of patients doing their exercises at home without the supervision of a physiotherapist.
[25]	The fact that the Android version used in the study potentially leads to the exclusion of people who are likely to use old-generation mobile phones, the use of the latest Android 5.0 lollipop version raises the general affordability problem and the digital skill problem of people who will use this application at home.

Accuracy and reliability and results of the measurement characteristics of the studies examined are given in Table 2. Limitations of the reviewed studies are given in Table 3.

Discussion

This review provides a comprehensive overview of 13 articles currently available for the study of sagittal plane movements of the knee with wearable sensors, along with hardware features and measurement capabilities (accuracy and reliability), and to determine clinical application.

Continuous and inconspicuously monitoring of kinematic parameters (e.g., range of motion or peak knee flexion/extension angle during the stance phase) can provide important information in determining changes in individuals' health status and in rehabilitation and/or pharmacological treatments [26]. The use of these systems provides clinicians with the opportunity to closely track the joint healing process and develop personalized, optimal rehabilitation programs to maximize the quality of life of individuals, the main goal of rehabilitation [22]. In addition, the systems provide feedback to the person about their situation, and it is an important support for the participant to reach the predicted goal regarding the quality and completion of the exercises and can also be used to monitor therapy dosage and range of motion throughout the inpatient intervention. At this point, combining sensors with mobile health systems is an important step; however, there is no standard clinical system for continuous knee angle measurement with mobile health devices.

Sensor-based wearable systems should be able to evaluate the individual's performance not only in rehabilitation outcome and progression, but also during activities of daily living. Because knee movement in daily activities can be highly variable, a sensor system needs to capture the rich variety of knee movements produced during an individual's daily movement [14]. Büttner et al. [14] showed in their study that the knee angle outputs of the sensor during various activities of daily living were consistent with those of the reference system, and the results were comparable between short- and long-term measurements. Also, non-physiological data outputs were few and sensor failure was not evident. This is promising in that wearable technologies provide accurate results about performance in daily life.

Complex tasks such as jumping are difficult to accurately analyze with wearable sensors due to the large ground impact force. For example, decreased knee flexion during landing from a jump is associated with higher peak moments at the knee joint [27]. It has been stated that MoJoXlab [28] could accurately calculate joint angles for such complex tasks, so it is recommended to be developed to calculate potentially other complex tasks and exercises. Islam et al. [16] also demonstrated that MoJoXlab [28] could use in a clinical setting for complex tasks such as walking, squatting, and jumping, and among a variety of participants, both healthy and participants with anterior cruciate ligament reconstruction.

There are accelerometers, gyroscopes, magnetometers and potentiometers as sensors in wearable devices related to the knee. Allseits et al. stated that the gyroscope is an adequate tool to measure the range of flexion and extension of the knee [20]. On the other hand, Joukov et al. [29] stated that for a complete motion evaluation and effective tracking, an accelerometer, a gyroscope, and a motion capture tracker should be combined in a single tracking unit.

Sensor systems could generally use by being mounted on the knee pad. However, problems such as incorrect palpation of anatomical landmarks or misalignment of the axis of rotation of the sensor during the calibration process have shown that the instrumented knee brace causes larger standard deviations than the reference system. Also, performing the calibration of the knee brace and the sensor with passive knee flexion causes the knee movement to differ in active and weight-bearing conditions such as walking, and this brings with it measurement errors. The elastic material properties of the knee pad can also cause sensor slippage. The stretching of the material may affect the of the actual movements of the legs. Knee angle measurement in terminal flexion and extension is the measurement most affected by this problem. Thus, absolute knee angle data should be interpreted with caution, especially for sagittal knee angle terminal values. However, the deviation value may be less critical as it measures total knee motion angle or changes in total knee angle based on relative data rather than absolute data [14]. All these reasons show that special attention is required for knee pads in which sensors are integrated.

Büttner et al. [14] in their study verbally questioned the adaptations of the participants to the knee brace, and the participants did not report discomfort when wearing an instrumented knee brace during single measurement sessions. Büttner et al. [14] used potentiometer in their study and measured sagittal knee motion during various activities during a mean monitoring time of 7.1 ± 0.8 hours, without any connectivity issues or malfunctions in data transmission.

Accelerometers are sensitive to varying acceleration and vibration modes. However, it can be problematic for mobile applications as it increases bandwidth requirements for mobile systems, and reduces sampling rate and battery life [30]. In measurements made with gyroscopes, it has high accuracy and sensitivity to motion in short measurement periods, while the error rate is high in long measurement periods [17].

Measurement accuracy is an important topic that requires deep research when investigating the diagnostic and evaluation potential of wireless sensors. Again, the repeatability of measurement results is another important factor that determines the validity of wireless sensors. Lisiński et al. [25] showed high reproducibility in the measurement results obtained in both normal and maximum velocity measurements in most of the subjects. Reproducible assessments of the degree of deviation of the knee joint from the flexion and extension trajectory are also very important. All deviations from the knee joint trajectory show possible joint instability [30, 31] or a mismatch of muscle activities affecting the joint [32] and hence the effect of fatigue [33]. Precise motor control and the ability to sense and or show the position of a joint are crucial factors in determining proper knee function. Again, Lisiński et al. [25] evaluated this in their study and evaluated the patients' ability to return to 60° of flexion and the speed used to reconstruct this angle, and found no significant difference between the results recorded for the left and right knee joint.

The results of most studies presented so far have been considered isolated tests (focusing on a single joint movement) and therefore did not affect the knee joint functions tested. However, in rehabilitation practices, exercises that work several joint and muscle groups are generally used instead of isolated exercises. So, it is also important to test and examine with sensors several global motor tasks that are vital to people's daily activities, such as sitting in a chair, standing up, lunging forward, and going up and down a step [25]. Lisiński et al.[25] demonstrated successful methods for monitoring exercises performed independently in their studies.

When the oscillating motion in the sagittal plane is rapid, the acceleration measured from the triaxial accelerometer is affected by the effect of gravity and cannot reflect the true flexion angle of the leg [22]. Gholami et al. [18] found that the sensor signal correlated highly with sagittal angles and less with non-sagittal angles. Also, in the same study, knee joint angles were more consistent in participants compared to hip and ankle, providing higher accuracy in estimating knee angles. In addition, soft tissue artifact and sensor limitations affect the estimation accuracy of knee angle in dynamic movements such as walking [19]. One study showed that angles measured during walking, especially at heel strike, have higher error rates than other kinematic parameters. The causes of error during heel strike are related to sensor technology and location and occur because the sensor is not designed to detect hyperextension of the knee joint. For fast speeds also with bigger errors have been reported significant differences in peak flexion angle during both the stance and swing phases [22]. However, Gholami et al. [18] achieved similar accuracy at fast and slow speeds. The flexibility of wearable sensors affects the sensor readings that occur during flexion and extension movements. If the difference in torque and sensor flexibility produced by the person is too low, the sensor torque retraction will be slow and the disparity between flexion and extension will widen. Conversely, high tension can alter gait kinematics or cause stiffness or discomfort by pulling on the skin [22].

Conclusion

As a result; knee angles are often an important outcome measure in the evaluation of biomechanical function for both clinical and research purposes. In many diseases such as stroke and osteoarthritis, abnormal knee flexion/extension patterns can be seen during the gait cycle in patients. Monitoring and tracking these kinematic changes can yield clinically relevant and relevant information and data on prognosis and treatment. This review contains important data on the points to be considered in the measurement of sagittal plane angles of the knee.

What Do We Expect In The Future?

Evaluation of participants' passive range of motion can provide individualized guidance on the limits to which knee angle data can be expected. Studies have measured not only isolated knee motion but also knee angles with other joints during daily activities, but data on long-term performance are scarce. Future studies should provide long-term follow-up. Reducing the number of sensors in measurements should be the goal of future research to avoid data and statistical complexity. Although the developed sensor devices are quite small and light, velcro straps or an elastic belt are required for skin contact. Converting the hardware to a chip in the future will be an important step in preventing sensor slippage and belt or soft tissue artifact. Again, it is recommended to develop algorithms that prevent soft tissue artifact to improve kinematic tracking. Future work should go towards ergonomic and functional arrangements of smart knee pads that differ in design, structure and material. Modifications are needed to prevent unwanted slack in the sensors, especially during dynamic movements such as running and walking. Again, studies should be carried out to search for a generalizable calibration procedure without the need for any user for sensor calibrations. Finally, advances in technology's wearability, usability, general appearance and feel, ease of use, time required, and clarity of training will further increase participants' interest in technology.

Scientific Responsibility Statement

The authors declare that they are responsible for the article's scientific content including study design, data collection, analysis and interpretation, writing, some of the main line, or all of the preparation and scientific review of the contents and approval of the final version of the article.

Animal and human rights statement

All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or compareable ethical standards.

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Conflict of Interest

The authors declare that there is no conflict of interest.

References

1. Gage BE, McIlvain NM, Collins CL, Fields SK, Dawn Comstock R. Epidemiology of 6.6 million knee injuries presenting to United States emergency departments from 1999 through 2008. Acad Emerg Med. 2012;19(4):378-385.
2. Papi E, Bo YN, McGregor AH. A flexible wearable sensor for knee flexion assessment during gait. Gait Posture. 2018;62:480–3.
3. Stratford PW, Kennedy DM, Robarts SF. Modelling knee range of motion post arthroplasty: Clinical applications. Physiother Can. 2010;62(4):378–87.
4. Fennema MC, Bloomfield RA, Lanting BA, Birmingham TB, Teeter MG. Repeatability of measuring knee flexion angles with wearable inertial sensors. Knee. 2019;26(1):97–105.
5. Toffola LD, Patel S, Ozsecen MY, Ramachandran R, Bonato P. A wearable system for long-term monitoring of knee kinematics. Proceedings of 2012 IEEE-EMBS International Conference on Biomedical and Health Informatics. 2012.p.188–91.
6. Loncar-Turukalo T, Zdravevski E, Machado da Silva J, Chouvarda I, Trajkovik V. Literature on wearable technology for connected health: scoping review of research trends, advances, and barriers. J Med Internet Res. 2019;21(9):e14017.
7. Atallah L, Jones GG, Ali R, Leong JJH, Lo B, Yang GZ. Observing recovery from knee-replacement surgery by using wearable sensors. In: 2011 International Conference on Body Sensor Networks. 2011.p.29–34.
8. Cooper G, Sheret I, McMillan L, McMillian L, Siliverdis K, Sha N, et al. Inertial sensor-based knee flexion/extension angle estimation. J Biomech. 2009;42(16):2678–85.
9. Schulze M, Liu TH, Xie J, Zhang W, Wolf KH, Calliess T, et al. Unobtrusive ambulatory estimation of knee joint angles during walking using gyroscope and accelerometer data - a preliminary evaluation study. In: Proceedings of 2012 IEEE-EMBS International Conference on Biomedical and Health Informatics. 2012.p.559–62.
10. Aroganam G, Manivannan N, Harrison D. Review on wearable technology used in consumer sport applications. Sensors (Basel). 2019;19(9):1983.
11. Brunner T, Lauffenburger JP, Changey S, Basset M. Magnetometer-augmented IMU simulator: in-depth elaboration. Sensors (Basel). 2015;15(3):5293–310.
12. Mengüç Y, Park YL, Pei H, Vogt D, Aubin PM, Winchell E, et al. Wearable soft sensing suit for human gait measurement. Int J Rob Res. 2014;33(14):1748–64.
13. Fasel B, Sporri J, Chardonnens J, Kroll J, Muller E, Aminian K. Joint ınertial sensor orientation drift reduction for highly dynamic movements. IEEE J Biomed Health Inform. 2018;22(1):77–86.
14. Büttner C, Milani TL, Sichting F. Integrating a potentiometer into a knee brace shows high potential for continuous knee motion monitoring. Sensors (Basel). 2021;21(6):2150.
15. Di Paolo S, Lopomo NF, Della Villa F, Paolini G, Figari G, Bragonzoni L, et al. Rehabilitation and return to sport assessment after anterior cruciate ligament ınjury: Quantifying joint kinematics during complex high-speed tasks through wearable sensors. Sensors (Basel). 2021;21(7):2331.
16. Islam R, Bennasar M, Nicholas K, Button K, Holland S, Mulholland P, et al. A nonproprietary movement analysis system (mojoxlab) based on wearable ınertial measurement units applicable to healthy participants and those with anterior cruciate ligament reconstruction across a range of complex tasks: Validation study. JMIR Mhealth Uhealth. 2020;8(6):e17872.
17. Huang YP, Liu YY, Hsu WH, Lai LJ, Lee MS. Monitoring and assessment of rehabilitation progress on range of motion after total knee replacement by sensor-based system. Sensors (Basel). 2020;20(6):1703.
18. Gholami M, Rezaei A, Cuthbert TJ, Napier C, Menon C. Lower body kinematics monitoring in running using fabric-based wearable sensors and deep convolutional neural networks. Sensors (Basel). 2019;19(23):5325.
19. Hullfish TJ, Qu F, Stoeckl BD, Gebhard PM, Mauck RL, Baxter JR. Measuring clinically relevant knee motion with a self-calibrated wearable sensor. J Biomech. 2019;89:105–9.
20. Allseits E, Kim K, Bennett C, Gailey R, Gaunaurd I, Agrawal V. A novel method for estimating knee angle using two leg-mounted gyroscopes for continuous monitoring with mobile health devices. Sensors (Basel). 2018;18(9):2759.
21. Liu K, Yan J, Liu Y, Ye M. Noninvasive estimation of joint moments with ınertial sensor system for analysis of sts rehabilitation training. J Healthc Eng. 2018;2018:6570617.
22. Oubre B, Daneault JF, Boyer K, Kim JH, Jasim M, Bonato P, et al. A simple low-cost wearable sensor for long-term ambulatory monitoring of knee joint kinematics. IEEE Trans Biomed Eng. 2020;67(12):3483–90.
23. Turner AJ, Carroll W, Kodithuwakku Arachchige SNK, Saucier D, Burch V RF, Ball JE, et al. Closing the wearable gap—Part VIII: A validation study for a smart knee brace to capture knee joint kinematics. Biomechanics. 2021;1(1):152–62.
24. Bell K, Onyeukwu C, McClincy M, Allen M, Bechard L, Mukherjee A, et al. Verification of a portable motion tracking system for remote management of physical rehabilitation of the knee. Sensors (Basel). 2019;19(5):1021.
25. Lisiński P, Wareńczak A, Hejdysz K, Sip P, Gośliński J, Owczarek P, et al. Mobile applications in evaluations of knee joint kinematics: A pilot study. Sensors (Basel). 2019;19(17):3675.
26. Boyer KA. Biomechanical response to osteoarthritis pain treatment may ımpair long-term efficacy. Exerc Sport Sci Rev. 2018;46(2):121–8.
27. Leppänen M, Pasanen K, Krosshaug T, Kannus P, Vasankari T, Kujala UM, et al. Sagittal plane hip, knee, and ankle biomechanics and the risk of anterior cruciate ligament ınjury: A prospective study. Orthop J Sports Med. 2017;5(12):232596711774548.
28. Islam R, Bennasar M, Nicholas K, Button K, Holland S, Mulholland P, et al. A nonproprietary movement analysis system (mojoxlab) based on wearable ınertial measurement units applicable to healthy participants and those with anterior cruciate ligament reconstruction across a range of complex tasks: Validation study. JMIR Mhealth Uhealth. 2020;8(6):e17872.
29. Joukov V, Karg M, Kulic D. Online tracking of the lower body joint angles using IMUs for gait rehabilitation. Annu Int Conf IEEE Eng Med Biol Soc. 2014;2014:2310-2313.
30. Zlotnicki JP, Naendrup JH, Ferrer GA, Debski RE. Basic biomechanic principles of knee instability. Curr Rev Musculoskelet Med. 2016;9(2):114–22.
31. Kim HY, Kim KJ, Yang DS, Jeung SW, Choi HG, Choy WS. Screw-home movement of the tibiofemoral joint during normal gait: three-dimensional analysis. Clin Orthop Surg. 2015;7(3):303.
32. Knoop J, Dekker J, van der Leeden M, van der Esch M, Thorstensson CA, Gerritsen M, et al. Knee joint stabilization therapy in patients with osteoarthritis of the knee: A randomized, controlled trial. Osteoarthritis Cartilage. 2013;21(8):1025–34.
33. Gillot T, L'Hermette M, Garnier T, Tourny-Chollet C. Effect of fatigue on functional stability of the knee: particularities of female handball players. Int J Sports Med. 2019;40(07):468–76.

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